Electrons.[1]

By Sir William Bragg, K.B.E., F.R.S.

II.

Keeping in mind the results already described, we can now appreciate a very remarkable development of electron theory which has been made in the last few years. Spectrum analysis has long been occupied with the extraordinary complications of the light radiation emitted by the various atoms. As a result it appears that the frequencies of the lines in a spectrum often display curious and exact numerical relations, in the form generally involving differences of frequencies of similar lines or groups of lines. For instance, the famous Balmer equation:—

$$\text{Frequency} = \nu = \text{N}(1/n_1^2 - 1/n_2^2),$$

where $\text{N} = 3{\cdot}290 \times 10^{15}$, gives the frequencies of series of lines in the hydrogen spectrum. When n_1 is put equal to 2, and n_2 to 3, 4, 5 in succession, the series of values for ν represent the frequencies of the lines in the visible spectrum. If

$$n_1 = 3 \text{ and } n_2 = 4,\ 5,\ 6,\ \ldots,$$

in succession, we have the frequencies of lines in the infra-red (Paschen); and if

$$n_1 = 1,\ n_2 = 2,\ 3,\ 4,\ \ldots,$$

we have the frequencies recently shown by Lyman to exist in the ultra-violet.

Now there is nothing in our older conception of the origin of radiation within the atom to give us a clue as to why differences of frequencies should come into these empirical, though most useful, formulæ. We have pictured to ourselves vibrating systems, mechanical or electric, and waves arising therefrom. But what connection between masses or electricities gives us in any simple way equations involving the addition or subtraction of frequencies? We are in a blind alley. Let us, therefore, abandon our preconceptions as to the origin of those lines which we find in the light spectrum and suppose that here also they arise in the same fashion as we actually know that they arise in the cases we have considered above. Suppose that the energy of an emission of radiation is derived from the energy of an electron. It may be the only way in which radiation ever does arise, but it is not necessary to suppose so much at present. It is enough that we carry into the atom the whole process which in X-rays and the photo-electric effect we have observed to take place in part outside. Suppose that within the atom there are certain positions or conditions in which electrons *may* be, each postulating a certain energy associated with the electron; and suppose that sometimes an electron slips from one position to another of lower energy, and that the difference in energies is transformed into wave radiation according to the same law as before, *i.e.* energy transferred $= h \times$ frequency. Let the energy in these states be $\text{N}h/1^2$; $\text{N}h/2^2$; $\text{N}h/3^2$; etc., and so on. Then all the series yielded by the Balmer formula are accounted for at the same time.

What may these states be? Why not, as Bohr suggests, so many different orbits in which electrons can move round the central positive nucleus in the atom, the nucleus the sure existence of which Rutherford has established? At one time, if we had presumed the existence of these orbits, we should have been inclined to connect them with the direct emission of radiation, and the frequency of that radiation would be the number of revolutions in a second. But now we assume these orbits to persist without radiation, and that radiation arises where the electron steps from one orbit to another; moreover, the frequency of the issuing radiation is determined by the simple rule: Frequency is equal to change of electron energy divided by h. We are not picturing any new process here, or evolving new ideas to fit awkward facts; we are supposing a process to exist in one place which we already know to exist in another.

It is a very remarkable fact that the number N is equal to $2\pi^2 me^4/h^3$ within small errors of experiment. Spectrum measurements show that N is equal to $3{\cdot}29033 \times 10^{15}$; and $2\pi^2 me^4/h^3$ is equal, taking the most recent determinations of m, e, and h, to $3{\cdot}289 \times 10^{15}$. Imagine an electron revolving in a circle about the positive nucleus of the hydrogen atom according to the orthodox laws of dynamics with kinetic energy $2\pi^2 me^4/n^2h^2 = \text{N}h/n^2$. Its velocity, v, is $2\pi e^2/hn$; the radius, r, of the circular orbit is found by putting $mv^2/r = e^2/r^2$, and is equal to $n^2h^2/4\pi^2e^2m$. The angular momentum is $mvr = nh/2\pi$. If the electron changes its orbit from $n = n_2$ to $n = n_1$, where n_2 is greater than n_1, its kinetic energy in the new orbit is *greater* than in the old by $\text{N}h(1/n_1^2 - 1/n_2^2)$. But an amount of potential energy has been set free equal to $e^2(1/r_1 - 1/r_2)$, and this is equal to twice the change in kinetic energy, as is easily seen by substituting for the r's their values as found above. Consequently, the right amount of energy is available for radiation. We can, therefore, following Bohr, define the necessary separate states as those of motion in circular orbits in which the angular momentum is an integral multiple of $h/2\pi$. The simplicity of these expressions is very attractive. But the matter is far from ending here. During the last few years Bohr and Sommerfeld have led an inquiry into the possibilities of this theory which has produced very remarkable results. These are due to a slight modification in the original conception. The different circular orbits which Bohr first pictured have become groups of orbits fixed by laws which are somewhat arbitrary, but not without foundation. A group contains a limited number of orbits in which the electrons may move, and each group corresponds to one of the original circular orbits. Some of the orbits in each group are elliptical. It appears that the energy of the electron would be the same in all the orbits of any one group were it not that when an electron moves in an ellipse its velocity is not always the same. Now a fast-moving electron shows a variation in mass when its speed alters, and this does affect slightly the energy of the orbit. Consequently, the electron that steps from an orbit belonging to one group to an orbit belonging to another group may part with an amount of energy which is not always exactly the same. The frequency of the consequent radiation may, therefore, have two or more values differing slightly from each other: the single spectrum line is doubled or trebled. This is what Sommerfeld calls the "fine structure" of the lines.

---

[1] The Twelfth Kelvin Lecture delivered before the Institution of Electrical Engineers on January 13. Continued from p. 82.

Now there is far more than mere speculation in this. The formula which Sommerfeld gives as the result of an analysis which is as reasonable as can be expected does more than account for known effects; it has predicted the existence of numerous lines, and even their intensities, and the predictions have been verified by experiment in the most remarkable way. The story is told in Sommerfeld's work on "Atom-building": a story of the work of himself, Bohr, and others during the last six years or so.

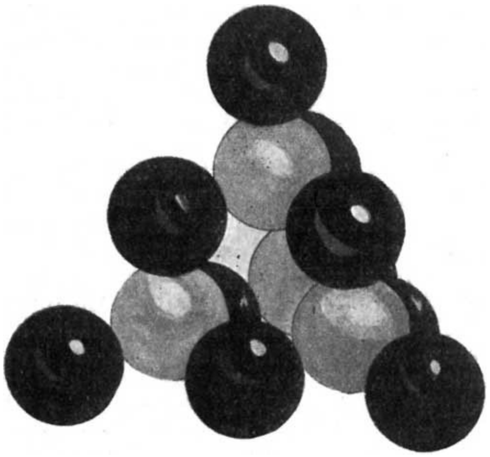

FIG. 2.—Model of the arrangement of carbon atoms in the diamond. All the atoms are alike, but those represented by light spheres differ in orientation from those represented by dark spheres.

We see that in this fundamental inquiry into the nature and properties of radiation the electron plays a very direct and important part. Our eyes are designed to detect waves, not electrons, and so our first attention is directed to radiation in wave form. But we now find that radiation energy may alternatively be carried by electrons, and that many things become clearer when we appreciate this fact. We can make further progress in our understanding of radiation, and indeed in our understanding of the electron, only by getting to know more about the reciprocal conversion of one form of energy into the other, since evidently it is one of the most frequent and most fundamental operations in Nature.

So far our conception of the structure of an atom would consist of a positive nucleus and of electrons attached thereto in some way, with the further idea that the energy attached to these electrons can have only certain definite values. Bohr assumes that they have these values because they can move round the core in certain orbits only, and Sommerfeld enlarges this idea, as already explained. But, of course, this can be no more than a partial picture of the whole atomic structure. The atom so conceived cannot fill the part required of it in the building of molecules and crystals.

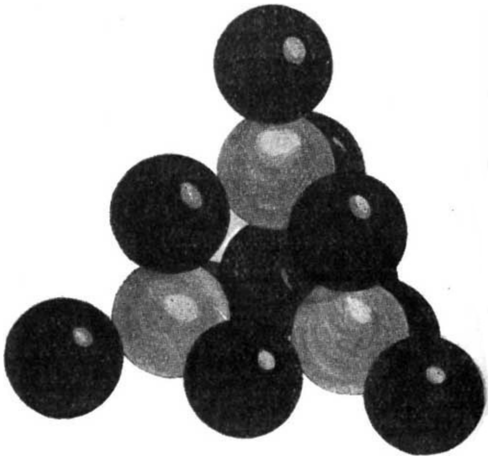

FIG. 3.—An extra ball can be inserted in the model without disturbing other balls.

When we come to examine these structures we find atoms attaching themselves to each other through the action of forces which cannot always be considered as acting from centre to centre. For instance, the arrangement of the carbon atoms in a diamond, as recently determined by X-ray methods, is such that every atom is at the centre of gravity of four others, arranged round it in tetrahedral fashion, as shown in the model. The representation of an atom by a smooth sphere and nothing more would be in agreement with the idea that the properties of the atom in any one radial direction are exactly the same as in any other radial direction, and that any forces between two atoms are between centre and centre. But if that were the case, the carbon atoms would pack themselves together more closely than they do. As a matter of fact, if the top of this model is lifted, another carbon atom can be inserted and the top replaced exactly as it was. If a more extensive model were employed, it would be seen that just twice as many atoms could be packed into any volume as are already there. We must conclude that there are definite subcentres of force on the outskirts of the atom, and that in the carbon atoms of which the diamond is composed there are four such sub-centres arranged symmetrically—that is to say, in tetrahedral fashion round the core.

Must not these sub-centres be electrons? And if so, must we not take them to be circulating in small orbits about a local centre? Or, perhaps, as Parson has suggested, the electron is ring-shaped, the electricity revolving round the axis of the ring. In this way we should have electromagnetic forces to link the atoms together.

It is very interesting to observe that, in any case, the carbon atoms in the diamond are not all oriented in exactly the same way. Taking a cleavage or tetrahedral plane as that of reference, half the atoms will be pointing towards the plane and the other half pointing away. This ought to make a difference to the X-ray spectra, and it has been looked for at various times, but without success. Lately, however, the improvement in the X-ray spectrometer has been considerable, and I now have no difficulty in finding the expected effect.[2] It is clear, I think, that the carbon atom in the diamond is to be represented as to its properties by a tetrahedron, and that the atom has different properties in different directions, or, as the chemist would say, has directed valencies. There can be little doubt that this is so in all atoms. The suggestion is that some of the electrons in an atom forming part of a crystal are tied down to certain regions on the surface, and that not all, if indeed any, of them are at all times revolving round the central core.

When atom joins up to atom it is these sub-centres that are at work; and since atom to atom and again atom to atom make in the end the crystal, and since the crystalline structure is the basis of all solid structure, and is fundamentally concerned with the strength of materials and their temper and all their physical properties, it is easy to see how great is this minute study of the electron.

If this conception of fixed electrons seems to clash with the orbital motions of Bohr and Sommerfeld, we must remember that the clash is between two pictures both of which are, we know, imperfect. We may expect that on the next occasion when a lecturer tries to tell you what advance has been made in the study of electrons some of these contradictions will have disappeared. Whether it will so turn out or not, I am sure of this, that in the attempt to realise the properties of Nature's unit, the electron, we are working in the true direction towards an understanding of the great problems of radiation and of material structure.

---

[2] There is, in fact, a small second-order spectrum in the reflection of X-rays by the tetrahedral plane.

Reformed Cannibals.[1]

NEW GUINEA, despite the considerable amount of attention that has been paid to it, has still large areas unexplored, and many peoples about whom nothing is known. Extremely little, even in the "Annual Reports of New Guinea," has been written about the natives of the D'Entrecasteaux group, the large mountainous islands which lie off the north coast of the south-eastern end of New Guinea, although a good deal of information has been collected about some of the peoples on the adjacent mainland and about the Trobriand Islanders farther east. An ideal opportunity was thus open to Mr. Jenness, a distinguished classical student of Balliol, who was one of the first to obtain the Oxford diploma in anthropology. A further advantage he had was in the collaboration with his brother-in-law, the Rev. A. Ballantyne, who for nine years had been a missionary on Goodenough Island.

The result of this partnership is a pleasantly written, sympathetic account of the Goodenough Islanders, which fills up one of the many gaps in our knowledge of the ethnology of New Guinea. The authors have given a succinct account of native life from the economic, social, and psychical points of view, and it is a comfort to students at home to feel that they have here something on which they can rely implicitly. Specialists will naturally turn to particular chapters, but all should read the book through in order to get a complete view of the mode of life, actions, ideas, and ideals of the people; these are all interdependent and cannot satisfactorily be studied apart.

We may perhaps attribute the conciseness of the book to the present cost of book-production, but a little more detail in various sections would have added to its value. We are, however, given the hope that other matter may be published later; we trust that this will be the case, and that the material culture will receive fuller treatment, for we learn that the collections have now reached the Pitt-Rivers Museum. We should also like to hear more about the stone sitting-places and their connection with cannibalism, and about the use of memorial- and grave-stones, as these are doubtless connected with one of the great culture migrations into Oceania. Evidently it was not the intention of the authors to enter into the thorny paths of racial or cultural migrations, or even to give parallels among neighbouring people; so they have rigidly confined themselves to what they have themselves noted, and this is all that we can demand of them. A field-observer who is alive to the wider problems will usually be able to appreciate the value of small details which might otherwise be overlooked or considered as too trivial to mention; but in any case generalisation should not be mixed up with description, and our authors have not fallen into this common practice.

The curious custom of chopping off a finger-

---

[1] "The Northern D'Entrecasteaux. By D. Jenness and the late Rev. A. Ballantyne With a preface by R. R. Marett. Pp. 219. (Oxford: At the Clarendon Press, 1920.) 12s. 6d. net.